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Type-I intermittency route to chaos in passively Q-switched Tm:YLF laser emitting at 2.3 µm

Hippolyte Dupont[1], *Matthieu* Glasset[1], *Pavel* Loiko[2], *Patrick* Georges[1], *and Frédéric* Druon[1,*]

[1]Université Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry, 91127 Palaiseau, France
[2]Centre de Recherche sur les Ions, les Matériaux et la Photonique, UMR 6252 CEA-CNRS-ENSICAEN, Université de Caen, 6 Boulevard Maréchal Juin, 14050 Caen Cedex 4, France

Abstract. We report on an original chaotic dynamic behaviour of a passively Q-switched 2.3-µm Thulium laser operating on the $^3H_4 \rightarrow {}^3H_5$ transition. The experiment employs a Tm:LiYF$_4$ laser crystal within various laser cavity configurations, involving optional additional cascade laser operation on the $^3F_4 \rightarrow {}^3H_6$ transition at 1.9 µm. The saturable absorber employed is Cr^{2+}:ZnSe, which is exclusively saturated by the 2.3 µm laser emission. A precise analysis of the Q-switching dynamics shows a pronounced inclination of the cascade laser scheme towards chaotic operation. To investigate the origins of chaos, we originally monitor the metastable $^3F_4$ level population using cascade laser operation at 1.9 µm, which proves to be a crucial underlying parameter for explaining the observed instabilities. This analysis allows for explaining the specific dynamics of the Q-switched 2.3 µm Tm-laser intrinsically linked to Tm^{3+}-doped materials. A very atypical route to chaos for a Q-switched laser is demonstrated involving type I intermittencies. The obtained results are of great interest for studying the premises of chaos in pulsed solid-state lasers.

1 Introduction

The study of chaotic dynamics holds great interest as it deepens our comprehension of laser stability issues. Rare-earth ion-based lasers operating above 2 µm indeed have in this matter a strong propension to reach chaotic regimes, since such materials often involve cascade energetic transitions. In the case of Tm^{3+}-doped materials, the $^3H_4 \rightarrow {}^3H_5$ laser transition at 2.3 µm (the wavelength of interest in the present work) is indeed linked to the $^3F_4 \rightarrow {}^3H_6$ transition corresponding to emission at 1.9 µm via the long luminescence lifetime (*e.g.*, 11 ms in Tm:LiYF$_4$) of the intermediate metastable level $^3F_4$. We demonstrate here, for the first time to our best knowledge, that a type-I intermittency route to chaos can be observed within a single Q-switched cavity, which is a very atypical route to chaos for Q-switching. This particular chaotic behaviour with intermittency appears to be intrinsically linked to the cascade laser scheme, as predicted in [1].

2 Laser architecture

This work presents a detailed examination of the dynamic behaviour of a Tm:LiYF$_4$ (Tm:YLF) laser operating on the $^3H_4 \rightarrow {}^3H_5$ transition, emitting at 2.3 µm alone or in cascade laser scheme (*i.e.*, simultaneously at 2.3 µm and 1.9 µm). For this, a Q-switched cavity operating at 2.3 µm using a Cr:ZnSe crystal as saturable absorber is employed, Fig. 1(a). An optional CW cavity supporting oscillations at 1.9 µm overlapping with the Tm:YLF crystal is also implemented to compare laser dynamics with and without cascade laser operation. In these configurations, passively Q-switch regime is obtained with a repetition rate ranging between 1 and 30 kHz and a nearly pump-independent pulse duration of 4.7 µs.

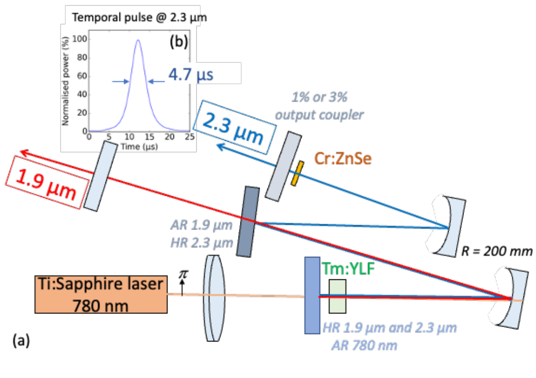

Fig. 1. 2.3-µm Tm:YLF laser passively Q-switched by a Cr:ZnSe saturable absorber: (a) laser setup; (b) an oscilloscope trace of a single Q-switched pulse.

The pulse repetition rate of the Q-switched Tm-laser, as expected, linearly increases with the pump power, Fig. 2. Here, the error bars indicate the r.m.s. value of the repetition rate measurements. Chaotic zones can be clearly identified when the dispersion of the repetition rate explodes [2] in both cases (with or without cascade laser operation). On the opposite, stable zones occur with relatively low dispersion in the repetition rate. We will focus now on the transition regime from stable passive Q-switching to the chaotic regime observed around the repetition rate of 20 kHz. To analyse different regimes, we

* Corresponding author: frederic.druon@institutoptique.fr

plot in Fig. 3(a) the oscillograms of pulsed 2.3-µm laser emission. Further analysis is possible by extracting from these oscillograms the pulse peak powers which allows one to access to interesting parameters for studying chaos, such as entropy and Poincaré maps, Fig. 3(b). In the intermittency regimes [3, 4], it is then possible to observe *L*~7-long laminar phases and estimate the distance (e = 0.018) between the Poincaré map and the bisector line, corroborating the type-I intermittencies by finding the law $L = e^{-\lambda}$, with λ very close to the expected value of 0.5.

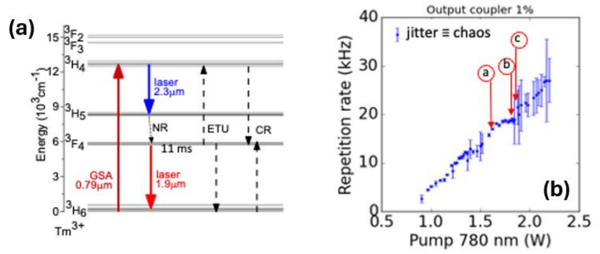

Fig. 2. (a) Energy-level scheme of Tm^{3+} ions showing pump and laser transitions and relevant spectroscopic processes (CR – cross-relaxation, ETU – energy-transfer upconversion); (b) passively Q-switched cascade Tm:YLF laser: pulse repetition rates vs. pump power, for 1% output coupling; the error bars represent the r.m.s. deviation.

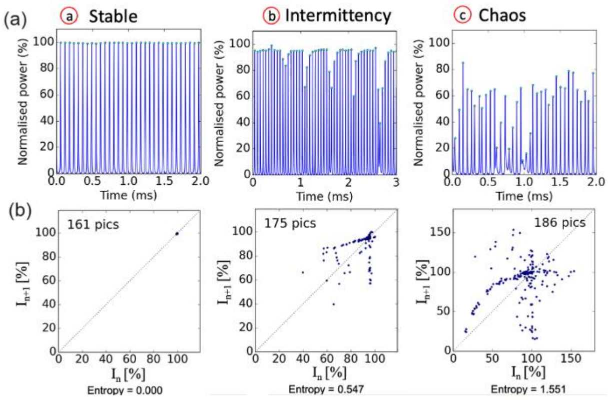

Fig. 3. Passively Q-switched cascade Tm:YLF laser with 1% output coupling: (a) oscilloscope traces of laser emission at 2.3 µm and (b) Poincaré maps of the peak intensities $I_{n+1} = f(I_n)$ for three different regimes (from left to right): single-pulse stable Q-switching, intermittency regime, chaotic regime.

3 Cascade laser operation

The developed laser setup allowed us to simultaneously access the temporal behavior of 2.3-µm and 1.9-µm lasers which represents an innovating approach to monitor the metastable level population. This approach enabled us to compare the sensitivity of two laser transitions of Tm^{3+} ions to dynamic instabilities. Figure 4 represents the concomitant recording of these two laser emissions for three different regimes: i) a stable regime, when both 2.3-µm and 1.9-µm lasers synchronously oscillate in a regular way, ii) isolated intermittencies and iii) a 4-pulse periodic transient regime. It is noticeable that the 1.9-µm Tm-laser which is formally considered as continuous-wave as its emission is not modulated by the saturable absorber appears more unstable than the Q-switched 2.3-µm laser. For example, in the stable Q-switching regime, relaxation oscillations of the 1.9-µm laser do not impact the pulse train stability at 2.3 µm, and even more representative, after an isolated intermittency whereas the Q-switching instantly comes back to a stable regime, the 1.9-µm laser remains remarkably unstable, as shown in the panel "isolated intermittencies" of Fig. 4.

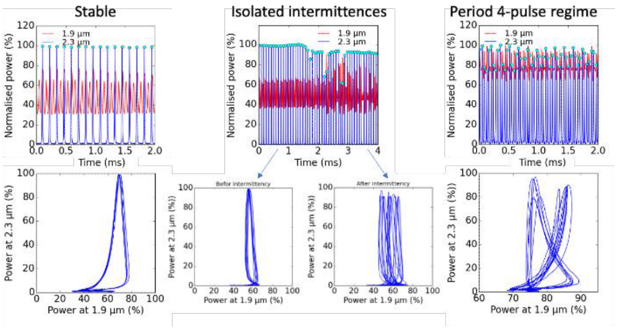

Fig. 4. Simultaneous monitoring of two laser emissions from the passively Q-switched cascade Tm:YLF laser: Q-switched 2.3-µm laser (in *blue*) and formally continuous-wave (free-running) 1.9-µm laser (in *red*). *Upper* line, oscilloscope traces of laser emission. *Lower* line, the plot of 2.3 µm laser peak power versus that at 1.9 µm.

4 Conclusion

In conclusion, the analysis of intermittent dynamics provides valuable insights into complex systems, contributing to our understanding of fundamental principles underlying natural and engineered systems such as cascade lasers emitting in the mid-infrared spectral range. In the context of this study, the fact that Tm^{3+}-based laser systems are prone to intermittent chaotic transitions makes Q-switched lasers using such sources an interesting subject of investigation. These discoveries enhance our understanding of the intricate dynamics of Tm-lasers, impacting the design and optimization of MIR-range lasers for diverse applications, with potential extensions to other cascade lasers.

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